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OPTIMUM ECONOMIC LAYOUT OF FOREST HARVESTING WORK ROADS

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and David B. Brown

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ABSTRACT

Describes development of a model that can be used to optimize the spacing of work roads used primarily or exclusively for logging. Past methods have not included enough of the variables influencing cost. Road costs associated with the effects of variables of slope and difficulty of construction (primarily percentage of rock in the excavation) have not been included.

All direct costs associated with roads, landings, skidding, and yarding are included in the model to insure true economic optimization of road and landing spacings.

INTRODUCTION

The timber industry generally has applied modern techniques of management to such things as plant location, layout, and materials handling. However, the logging segment of the industry has been rather slow in adopting modern techniques, and there is still much room for improvement.

In the past several years, logging research efforts have increased and some improvements in logging and associated activities have been realized. Much more effort is needed before maximum efficiency in these areas can be attained.

The objective of this paper is to develop a model that includes work roads in the optimization of skidding methods. A work road is generally used only for harvesting and is usually not added to the permanent system. Although the solution to this model requires a computer, it is known that many modern loggers have either direct or indirect access to computers for payroll and accounting purposes, or for other uses, and its use would not present a special problem for most of the potential users.

Although it is recognized that other constraints such as impacts on the environment (i.e., where they are significant and can be adequately appraised) could be the deciding factors in some cases, only the direct cost of logging is included in this analysis. It is believed, however, that the model presented here can be useful for forest areas where these environmental impacts are relatively insignificant. Also, this model will eventually be extended by our project to include other constraints.

One of the earliest attempts to optimize the spacing of logging roads was presented by Matthews (1942) in his text on logging. Lussier (1961) showed how work road spacings can be optimized using some simplified models and the mathematics of calculus. For the lesser slopes (<20%), these methods of Matthews and Lussier give fairly good results when road construction and skidding costs are available. Seihei Kato's (1966, 1967) studies used a similar method of optimization. His studies were concerned with the density of roads within an entire forest area and therefore included all of the development roads. However, none of these analyses consider enough of the variables affecting cost. A more complete method is needed; otherwise the full economic potential cannot be attained.

Some of the recent research findings of Brown (1967) and Carter (1968) conducted for and in cooperation with the Intermountain Forest and Range Experiment Station's Forest Engineering Research Laboratory, Bozeman, Montana, provide the basis for a more complete analysis procedure.

Brown developed a method of determining the effects of selected variables on the cost of skidding or yarding. Carter developed cost equations for the principal variables that affect work road costs. In this paper, data from these two studies are combined in a model to optimize the total harvesting operation. A discussion of the general methods employed for each study follows.

Skidding and Yarding Studies

A rather large volume of field data on logging production has been obtained in the past 5 or 6 years for the equipment types and site conditions of the Rocky Mountain area. Analysis of early studies established data-collecting techniques and indicated other variables that would have to be included in the analysis. In his early studies, Brown (1967) used an analysis of variance technique developed by Draper and Smith (1966) called "backward elimination procedure" to eliminate the less significant variables and retain those that would give an adequate representation of production. The variables of slope, distance, logs per thousand board feet, and timber stand density are used in most of our prediction (regression) equations. Several publications are available from the Intermountain Forest and Range Experiment Station in Ogden, Utah, reporting on the results of these studies (Gardner and Schillings 1969, Schillings 1969a, Schillings 1969b).

Forest Road Studies

A variety of problems related to the broad subject of forest roads is being studied at our laboratory; this includes design criteria both as related to economics and the environment, and the economics of forest roads associated primarily or exclusively with harvesting. As studies progressed, it became apparent that we would have to include road costs related to harvesting in the total logging cost. This was done by formulating equations to represent the cost of each component. The total cost equation was then optimized (cost minimized) by use of calculus. A description of how this was done follows.

OPTIMUM ROAD SPACINGS FOR HARVESTING

The development of cost equations required the identification of all of the component costs involved and the variables affecting these costs. The objective was to obtain the minimum cost of log removal as a function of the controllable system variables.

In every case, the removal of logs involves several processes including:

Roads and Landings:

1. Moving-in of construction equipment
2. Planning and layout of roads and landings
3. Construction of roads
4. Construction of landings

Skidding or Yarding:

1. Moving of skidding equipment
2. Setting up of equipment for each operation
3. Skidding of logs

The costs associated with the activities listed above are the function of several variables. These costs and variables are listed below:

I. *Cost to move in construction equipment*

C_1 = function of:

1. Distance moved
2. Type of equipment moved
3. Moving method used

II. *Cost to plan and lay out roads*

C_2 = function of:

1. Planning and layout method
2. Cost of men and materials
3. Productivity of the men
4. Length of road = function of:
    a. Road spacing
    b. Total area

III. *Cost of road construction*

C_3 = function of:

1. Cost of equipment (owning and operating, including cost of operators)
2. Production rate of equipment = function of:
    a. Sidehill slope
    b. Percent rock in excavation
3. Amount of road required = function of:
    a. Road spacing
    b. Road width

IV. *Cost of switchback construction*

C_4 = function of:

1. Cost of equipment (owning and operating, including cost of operators)
2. Production rate of equipment = function of:
    a. Sidehill slope
    b. Percent rock in excavation
3. Switchback size = function of:
    a. Radius of switchback
    b. Road width
    c. Backslope of cut
4. Number of switchbacks = function of:
    a. Road spacing
    b. Distance between switchbacks

V. *Cost of landing construction*

C_5 = function of:

1. Cost of equipment (owning and operating, including cost of operators)
2. Production rate of equipment = function of:
    a. Sidehill slope
    b. Percent rock in excavation
3. Landing size = function of:
    a. Timber volume per unit area
    b. Landing spacing
    c. Road spacing
4. Number of landings = function of:
    a. Landing size
    b. Volume of timber per unit area

VI. *Cost to move in skidding equipment*

C_6 = function of:

1. Distance moved
2. Type of equipment moved
3. Moving method used

VII. *Cost to set up skidding equipment*

C_7 = function of:

1. Skidding method
2. Setup time
3. Number of setups = function of:
    a. Road spacing
    b. Distance between setups

VIII. *Cost of skidding*

C_8 = function of:

1. Cost of skidding equipment (owning and operating, including cost of operators)
2. Volume of timber per unit area

3. Productivity of equipment = function of:

    a. Sidehill slope

    b. Number of logs per turn

    c. Size of the logs (in logs/MBF[1])

    d. Distance skidded to road

The above variables are summarized in table 1, showing the functional relationship and cost factors. The symbols used for each variable are also given.

The optimization of log removal required the consideration of two general cases (fig. 1). The *first case* involves harvesting a stand of timber that is accessible by contour work roads extending from an existing primary road (in the Rocky Mountain area, this is usually a climbing road), and the *second case* involves the construction of work roads that switch back and forth across the area to be harvested.

The *first case* is the simplest because the cost of switchbacks doesn't need to be considered in the total cost equation. The *second case*, which includes switchbacks, will be used in this analysis. When the model is used for the nonswitchback case, this cost factor can be removed.

The development of the eight cost equations will not be discussed here because of the lengthy details and space required for complete understanding. However, these equations are listed below. All costs are converted to a common unit of dollars per one thousand board feet ($/MBF). All distance measurements are in horizontal units. Values for productivity of construction equipment and productivity coefficients were derived from past records and studies.

Cost Equations

C_1 - Move-in, construction	$C_1 = Nc/AV$
C_2 - Road planning and layout	$C_2 = 43{,}560\ Dm/Pm\ Fm\ XV$
C_3 - Road construction	$C_3 = 43{,}560\ Dc\ Hr/Pc\ FVX$
C_4 - Switchback construction	$C_4 = \dfrac{43{,}560\ Dc\ Hr}{Pc\ VXF\ Zb+X\{(S^2/Mx^2)-1\}^{\frac{1}{2}}} + \dfrac{200\ Dc\ Hr}{Pc\ F}$
C_5 - Landing construction	$C_5 = 43{,}560\ Dc\ Hl/Pc\ VXY$
C_6 - Move-in, skidding	$C_6 = Ns/AV$
C_7 - Setup, skidding	$C_7 = 43{,}560\ Ds\ Sp/Zs\ VX$
C_8 - Skidding	$C_8 = [Dc/Ps\ Vc]\ [a_1+a_2S+a_3VcLv+a_4(dav.)]$

[1]MBF = 1,000 board-foot measure, log scale.

Table 1.--*Relationship of system variables to cost*

Symbol	Variable description	Units	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A	Total logging area	acres	x	x				x		
Dc	Construction method cost	$/hr.			x	x	x			
Dm	Layout method cost	$/hr.		x						
Ds	Skidding method cost	$/hr.							x	x
F	Productivity (construction)	yd.^{3}/hr.			x	x	x			
Fm	Productivity (layout)	ft./hr.		x						
Hl	Excavation/landing	yd./landing					x			
Hr	Excavation/ft. of road	yd./ft.-rd.			x					
Le	Landing length	feet					x			
Lv	Number logs/volume of timber	logs/MBF								x
Mx	Maximum road grade	decimal %			x					x
Nc	Move-in cost (construction)	$/move	x							
Ns	Move-in cost (skidding)	$/move						x		
Pc	Productivity coef. (const.)	none			x	x	x			
Pm	Productivity coef. (layout)	none		x						
Ps	Productivity coef. (skid)	none								x
Ro	Percent rock in excavation	decimal %			x	x	x			
S	Slope of sidehill	decimal %			x	x	x			
Sp	Time/setup (skidding)	hr./setup							x	
V	Timber volume/horiz. area	MBF/acre	x	x	x	x	x	x	x	x
Vc	Volume/skidding cycle	MBF/cycle								x
W	Road width	feet			x	x				
Wl	Landing width	feet					x			
X	Road spacing	feet		x	x	x	x		x	x
Y	Landing spacing	feet					x			x
Zb	Level road/switchback	feet				x				
Zs	Distance between setups	feet							x	
dav.	Average skidding distance	feet								x
$a_{1,2,3,4}$	Regression coefficients	none								x

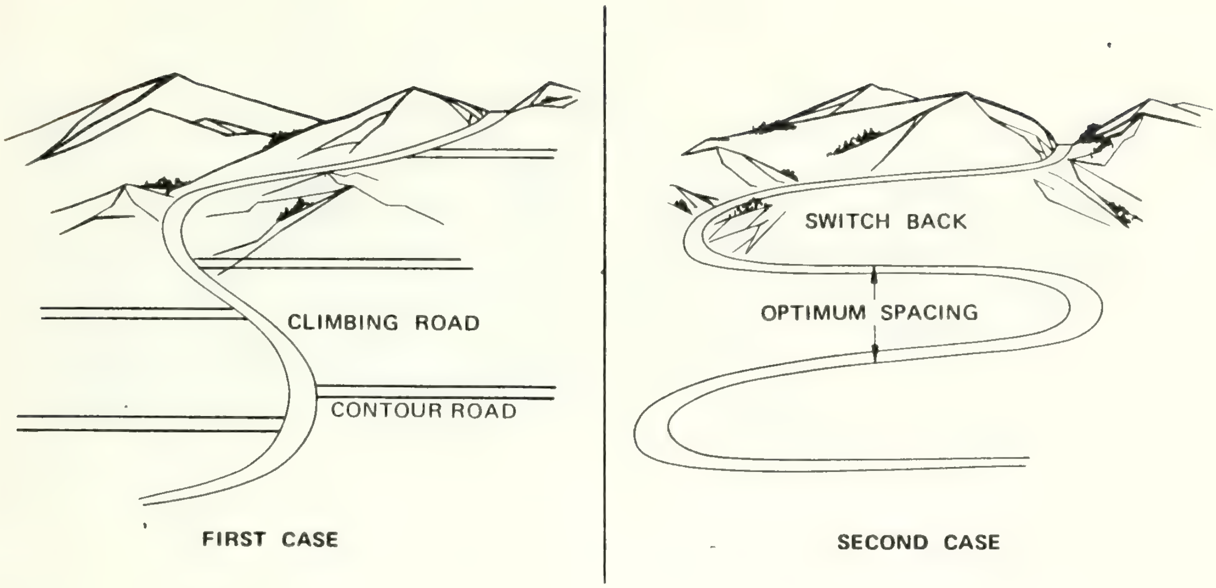

Figure 1.--Schematic of work road configurations for optimum spacing

The above expressions were summed into a total cost equation $C_t = \Sigma C_{1-8}$ that represents the average cost in dollars to remove one thousand board feet of timber from an area. The objective is to be able to select the construction and skidding methods that give a minimum value of total cost (C_t). The minimum value of C_t occurs at some unique value of road spacing or some unique combination of values for road and landing spacing. The first step in finding the optimum combination of methods is to find the layout or spacing that yields minimum cost for each possible combination. Then the combination that gives minimum total cost can be identified.

Because the objective was to find the optimum spacing of roads and landings, the partial derivatives for X (road spacing) and Y (landing spacing), when each equation was set to zero, were taken for the case of landings and no landings. This was done first for the case with no landings. The two equations were solved simultaneously, using iteration, to find the road and landing spacings that gave the minimum total cost of logging. An electronic computer was used for the solution; the flow diagram (fig. 2) shows how this solution is obtained. The computer program is in Fortran language written for an XDS Sigma 7 computer.[2]

[2]The Fortran program is available from the Forestry Sciences Laboratory located on the campus of Montana State University at Bozeman.

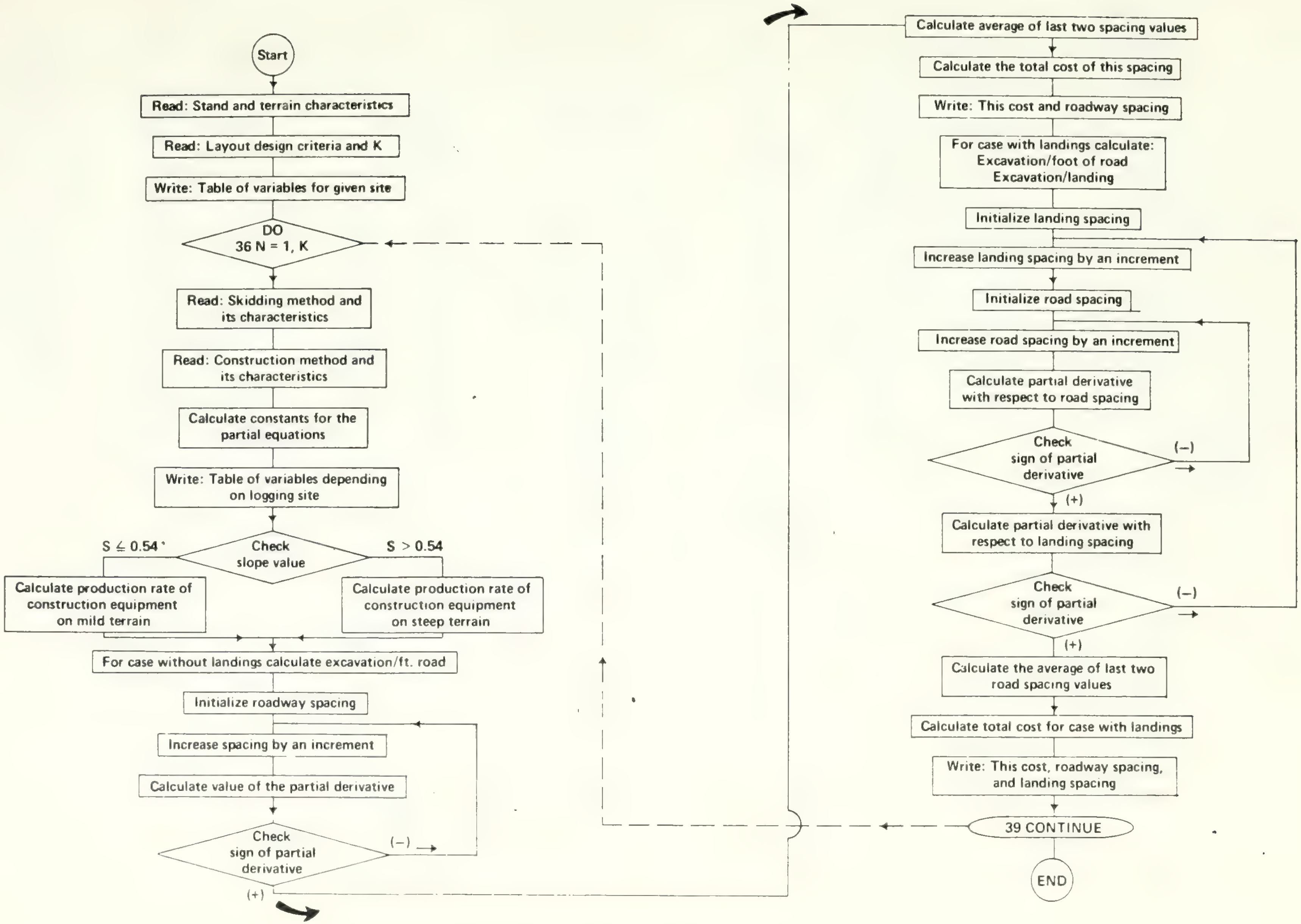

Figure 2.--Flow diagram used for solution to optimum logging work road spacing.

Example of Use

Use of the model developed in this paper will be illustrated by an example that is a typical situation in the northern Rocky Mountains. Also, it should be remembered that this model shares a common characteristic with any other model in that the results vary in direct proportion to the reliability of the inputs. For this example we will use the following values:

Terrain and Stand Characteristics:[3]

Ro, percent rock in excavation (decimal %)	=	0.20
S, sidehill slope (decimal %)	=	0.40
V, timber volume density in MBF/acre	=	20.0
Zb, level road in ft. per switchback	=	5,000
Lv, log size in logs/MBF	=	10.0
A, size in acres of total logging site	=	500.0
Mx, maximum road grade (decimal %)	=	0.06
Nc, cost in dollars to move-in construction equip.	=	$500.00
Ns, cost in dollars to move-in skidding equip.	=	$400.00

A large crawler tractor equipped with a ripper tooth will be used for road construction. The equipment and layout are as follows:

Layout:

Dm, cost of two-man crew in $/hr.	=	$10.00
Pm, coefficient of production of layout crew	=	0.75
Fm, productivity of layout crew in ft./hr.	=	500.0
W, road width in feet without landings	=	16.0
W, road width in feet with landings	=	12.0
Wl, landing width in feet	=	30.0
Le, length of landings in feet	=	100.0

Construction Equipment:

Pc, productivity coefficient of equipment	=	0.8
Dc/F, average cost of excavation in cu. yd.	=	$0.21

Two methods of skidding will be evaluated--a medium crawler tractor (61-80 DBHP)[4] and a large crawler tractor (110-130 DBHP).

Skidding Equipment:

Ds, cost in $/hr. to operate medium tractor	=	$14.00
Ds, cost in $/hr. to operate large tractor	=	$16.00
Ps, productivity coefficient for both methods	=	0.75
Sp, time in hrs. to set up the equipment	=	0.0
Zs, distance in feet between setups	=	0.0
Vc, volume in MBF/cycle of medium crawler	=	0.7
Vc, volume in MBF/cycle of large crawler	=	1.0

[3]All symbols are defined in table 1.
[4]DBHP = Drawbar horsepower.

Regression Coefficient for Skidding Equipment: (from Brown (1967))

Medium Crawler:

$a_1 = 0.10518$
$a_2 = 0.00201$
$a_3 = 0.01257$
$a_4 = 0.00027$

Large Crawler:

$a_1 = 0.10736$
$a_2 = 0.00133$
$a_3 = 0.01502$
$a_4 = 0.00048$

The computer output for this example follows (table 2), showing that the most economic cost method is a medium skidding crawler and road spacing of 675 feet, without landings. This solution, then, is the optimum for the conditions in the example.

Table 2.--*Results of skidding evaluation*

Construction method	Skidding method	NO LANDINGS Cost $/MBF	NO LANDINGS Horizontal road spacing	LANDINGS Cost $/MBF	LANDINGS Horizontal road spacing	LANDINGS Landing spacing
			Feet		*Feet*	*Feet*
Large Crawler	Medium Crawler	11.0020	675	11.0751	775	850
Large Crawler	Large Crawler	12,4045	575	12.6840	675	750

CONCLUSIONS

Modern management techniques to reduce the cost of logging have been used rather sparingly by the logging industry to date, compared with most other industries. It has been demonstrated here that they are useful techniques and can be employed to effect maximum savings (or minimize cost) for logging operations.

The use of these methods does not require complete understanding of the mechanics of development of the model, but only the correct application. The example presented in this paper illustrates this.

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1973. Optimum economic layout of forest harvesting work roads. USDA For. Serv. Res. Pap. INT-133, 13 p., illus. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

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OXFORD: 383.2:30. KEY WORDS: Logging, roadbuilding (temporary), optimization, harvesting, model.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah, (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

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